FOURIER ANALYSIS OF GAMMA-RAY BURST LIGHT CURVES: SEARCHING FOR DIRECT SIGNATURE OF COSMOLOGICAL TIME DILATION

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ABSTRACT

We study the power density spectrum (PDS) of light curves of the observed gamma-ray bursts (GRBs) to search for a direct signature for cosmological time dilation in the PDS statistics with the GRBs whose redshifts z's are known. The anticorrelation of a timescale measure and a brightness measure is indirect evidence of its effect. On the other hand, we directly demonstrate that a time dilation effect can be seen in GRB light curves. We find that timescales tend to be shorter in bursts with small redshift, as expected from cosmological time-dilation effects, and we also find that there may be non-cosmological effects constituting to this correlation. We discuss its implication on interpretations of the PDS analysis results. We put forward another caution to this kind of analysis when we statistically exercise with GRBs whose z is unknown.

Subject headings: cosmology:miscellaneous – gamma rays:bursts – methods:statistical

1. INTRODUCTION

Cosmological objects should not only be redshifted in energy but also extended in time because of the expansion of the universe. Time dilation is a fundamental property of an expanding universe. There have been interests in cosmological time dilation as an observational experiment where its effect is large, such as high-redshift quasar or supernova observations. In order to measure time dilation in light curves of the cosmological objects, it is necessary to find a way of defining the timescale and of characterizing the timescale of variation. The autocorrelation function has also been widely used for this purpose. A number of groups have looked for time dilation in quasar light curves and reported their

successes (e.g. Hook et al. 1994), but there seem other opinions on the detection (e.g. Hawkins 2001). A more direct observation of time dilation has come from the measurement of the decay time of distant supernova light curves and spectra (Leibundgut et al. 1996; Riess et al. 1997). The results so far published are very convincing and strongly imply that time dilation has been observed. Another cosmological object where one would expect to see a time dilation effect is the observed gamma-ray bursts (Paczyński 1992; Piran 1992).

Observations taken by the BATSE instrument aboard the *Compton Gamma Ray Observatory* have identified more than a few thousand gamma-ray bursts (GRBs) and shown that their angular distribution is highly isotropic implying that GRBs are at a cosmological distance (Paciesas et al. 1999). Observations of the afterglow of GRBs enable us to establish the fact that GRBs are indeed cosmological (Mao & Paczyński 1992; Meegan et al. 1992; Piran 1992; Metzger et al. 1997). If GRBs are at cosmological distances then the burst profiles should be stretched in time due to cosmological time dilation by an amount proportional to the redshift, $1 + z$.

Without knowing their redshifts, different groups (Norris et al. 1994; Mitrofanov et al. 1996; Che et al. 1997a,b; Lee & Petrosian 1997; Deng & Schaefer 1998; Lee et al. 2000) have investigated the correlation of the duration of bursts and the burst brightness in order to look for a signature of time dilation. There have been a number of claims by groups working on GRBs that time dilation is seen in the stretching of peak-to-peak timescales (Norris et al. 1994, 1995; Lee & Petrosian 1997; Deng & Schaefer 1998; Lee et al. 2000). The expected redshift range of order unity would result in a time-dilation factor of a few while the burst durations cover a large dynamic range from tens of milliseconds to thousands of seconds (Fishman & Meegan 1995). Therefore, a time-dilation effect can only be detected statistically. One of the most serious limits of previous works is that inferences are all *indirect* and possibly misleading since the redshifts of most GRBs are unknown. Norris et al.

(1994, 1995) searched for time-dilation effects by dividing the bursts into groups based on their peak count rate and comparing some measure of burst duration with peak count rate. They have claimed that brighter bursts had shorter durations than dimmer ones and that the difference between the average durations of bright and dim bursts was consistent with a time-dilation factor of about 2. If bursts were standard candles, dimmer bursts would be time-dilated more than brighter bursts, by a dilation factor $(1 + z_{\rm dim})/(1 + z_{\rm bright})$, where $z_{\rm dim}$ and $z_{\rm bright}$ are the redshifts of dim and bright bursts. However, finding cosmological time dilation signature in light curves of GRBs is disputed. For instance, Mitrofanov et al. (1996) finds no time dilation in BATSE using the aligned peak test, and Band (1994) has warned that an intrinsic burst luminosity function could easily produce similar effects. Even if there is a correlation between the duration measure and the brightness measure of the bursts, it is not clear that the argument can be inverted to provide convincing evidence for the existence of time dilation. Questions have been raised as to whether or not the time stretching that is found is due to the intrinsic correlation between pulse width and burst brightness for bursts drawn from a volume-limited sample (Brainerd 1994, 1997). Yi & Mao (1994) also noted that relativistic beaming in either Galactic halo or cosmological models can produce flux-duration relationships that might be consistent with the reported effects. Wijers & Paczyński (1994) suggested a way to distinguish between anticorrelations between flux and duration produced by cosmological time dilation and those produced by a decrease in burst density with distance, which is needed in a local extended halo model if the luminosity function is independent of distance.

It is clear that despite the numerous works published on the subject, time dilation of GRBs remains controversial. Here we present direct results on this topic which differ from those of previous works in two important ways. Firstly, we analyze the Fourier power spectra of a sample of GRB light curves to look for such an effect. It provides a significant advantage over other methods, which is relatively easy to interpret. All the timescales of

GRB variability are expected to show the effect of time dilation. We do not require to isolate one particular timescale to fit, which may cause artificial results. Secondly, we use light curves of the GRBs whose redshift z is known so that we are able to infer the time dilation effect directly. Statistical significance is reduced because of a small size of GRB data sets. Nonetheless we have a direct measure of time dilation, if it were, since we use the GRB light curves for z-known samples. The number of the GRBs whose z is measured is increasing steadily, and it is worth while to attempt directly confirming time dilation effects with the GRBs with redshift information.

2. PDS OF GRB LIGHT CURVES

We have used light curves of GRBs from the updated BATSE 64 ms ASCII database[1]. From this archive we select the light curves of the GRBs whose redshifts are available. We list up the GRBs used in our analysis with BATSE trigger numbers and the reported redshifts in Table 1. We divide our sample into two subgroups so that we separate near and far GRBs. We calculate the Fourier transform of each light curve of GRBs and the corresponding power density spectrum (PDS), which is defined by the square of the Fourier transform of the light curve. Before averaging the calculated PDSs in each subgroup, we normalize GRB light curves by setting their peak fluxes to unity. We compare the slopes obtained by the linear fits as it is without a time dilation correction with those after rescaling the individual GRB light curve to factor out $1 + z$. We have repeated the same process for the light curves of four different energy bands.

In Figure 1, we show the averaged PDSs for the two subgroups of the GRBs divided by the redshifts. Open triangles and squares represent the far GRBs ($z \gtrsim 1.5$) and the

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[1] $ftp://cossc.gsfc.nasa.gov/pub/data/batse/$

near GRBs ($z \lesssim 1.5$), respectively. For the far GRB subgroup power in lower frequencies is high, and for the near GRB subgroup power is concentrated in high frequencies. This is exactly what one may expect if light curves of GRBs are lengthened due to cosmological time dilation. Instead removing the individual Poisson noise of a burst from the individual PDS at high frequencies before averaging, we attempt power-law fits in the limited range, i.e., $-1.6 < \log f < 0$. The lower bound is determined in that the deviation from the power law begins due to the finite length of bursts. The upper bound is given such that the Poisson noise becomes dominant. In fact, this is the range where the Poisson noise can be negligible and consequently the subtraction of the noise can be ignored, as seen in Figure 2 of Beloborodov et al. (1998). Poisson noise of the time bin becomes important only at high frequencies, $f \gtrsim 1$ Hz. Besides, it is the range where the simple power-law can be applied (Beloborodov et al. 1998). Dashed lines and solid lines are the best fits obtained by least square fits for the far GRBs and the near GRBs, respectively. Before the fitting the averaged PDS is smoothed on a scale of $\Delta \log f = 0.2$. The slopes and standard deviations obtained by the linear fit is summarized in Table 2. Exact values of the obtained slopes are subject to the range used in the fitting process. However, the trend is hardly affected, that is, the subgroup of far GRBs results in the steeper slopes than the one of near GRBs. For all channels, the subgroup of the GRBs with higher redshifts result in exclusively steeper slopes compared with that with lower redshifts. The slopes of the channel 4 show that peaks in higher energy bands are narrow in general.

To see the effects of time dilation, we rescale the time interval of individual GRB light curve by a factor of $(1 + z)^{-1}$, where z is the redshift of the individual GRB. This should remove the effect of time dilation, that is, the difference of slopes in the two subgroups resulting from cosmological time dilation. This manipulation has the effect of shifting the contributions of all GRBs to the range of higher frequencies. Resulting slopes of the fits are shown in Figure 2 and summarized in Table 2. We note that the removal of the $(1 + z)$

factor makes discrepancies of slopes in two subsamples reduced indeed, but differences still marginally remain.

3. DISCUSSION

Claiming time dilation in light curves of GRBs with the anticorrelation of a timescale measure and a brightness measure has several difficulties. One difficulty is that this effect is correct only for standard candle sources with a standard duration, which we have evidence that it is not necessarily true (Kim et al. 2001; Chang & Yi 2001). A broad luminosity function and/or an intrinsic spread in the durations could smear out the signature. Another possible difficulty with this anticorrelation is that it could be mimicked by intrinsic properties of the sources (Brainerd 1994, 1997; Yi & Mao 1994; Wijers & Paczyński 1994). An additional complication is that an intrinsic redshift of the time profiles from higher energy bands to lower energy bands may be present (Fenimore & Bloom 1995), which would bleach the cosmological signature.

We investigate the correlation between redshifts and timescale measures using available GRB data with known z. Unlike past indirect searches for cosmological time dilation, we use the GRBs whose z is known at the expense of statistical significance. Diverse time scales shown in GRB light curves may result from cosmological time dilation of bursts, or from intrinsic properties of burst sources. The correlations among pulses within individual bursts give a measure of the intrinsic effects, while the correlations among bursts could result from both intrinsic and cosmological effects. We find that timescales tend to be shorter in bursts with small redshift, as expected from cosmological time-dilation effects, but we also find that there may be non-cosmological effects constituting to this correlation. The implication of our analysis is that light curves of the observed GRBs show both intrinsic and cosmological effects. It is shown from Figures 1 and 2 that removing time dilation

effect indeed reduces discrepancies in trend of time scale in the two subgroups divided by the redshifts. However, it is not clear that difference remained after taking into account a dilation effect is due to other effects pointed out previously (e.g., Brainerd 1994, 1997; Yi & Mao 1994). Because of the small number of data, it is inconclusive that these imperfect corrections require other explanations other than cosmological time dilation. The amount of observed stretching *may not* be the value expected from cosmological time dilation alone (Horack et al. 1996; Mészáros & Mészáros 1996). Challenging questions then are whether one may extract information on intrinsic properties of individual GRBs or whether one may distinguish a cosmological model by an analysis of the slope of the observed PDSs of GRBs.

Another important implication of our study should be pointed out. Beloborodov et al. (1998) applied the Fourier transform technique to the analysis of light curves of long GRBs. They claimed that, even though individual PDSs were very diverse the averaged PDS was in accord with a power law of index $-5/3$ over 2 orders of magnitude of a frequency range, and that fluctuations in the power were distributed according to the exponential distribution. With due care, the analysis of such kind may yield valuable information of the central engine of GRBs (Panaitescu et al. 1999; Chang & Yi 2000). However, the averaged power law index and the distribution of individual power should be corrected first in terms of a time dilation effect before making any physical points out of the results of the PDS analysis. We have followed similar procedures for the total sample as Beloborodov et al. (1998) did and obtained the slopes $-1.6074 \pm 0.105, -1.6423 \pm 0.099, -1.6876 \pm 0.094,$ and -1.2190 ± 0.086, from the channels 1 to 4, respectively, which are close to the reported value $-5/3$ indeed. However, these slopes become flatter when time dilation correction is made before the analysis, that is, $-1.5253 \pm 0.112, -1.5184 \pm 0.114, -1.506 \pm 0.122,$ and -1.222 ± 0.087, from the channels 1 to 4, respectively. This flattening can be also seen in Table 2, and is obviously expected if time dilation exists in light curves of the observed GRBs. Therefore, interpreting the power law index and its power distribution may not be straightforward,

unless we understand how the light curve is stretched or even contracted.

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Fig. 1.— Averaged PDSs of the two subgroups of the observed GRBs with known z are shown as a function of frequency in log-log plots. Power is in arbitrary unit and frequency is in Hz. Open triangles and open squares represent far and near GRB subgroups, respectively. Solid and dashed lines are the best fits of data. Four plots result from four different energy bands of BATSE experiments as indicated. Flat components at higher frequencies $f \gtrsim 1$ Hz show Poisson noise.

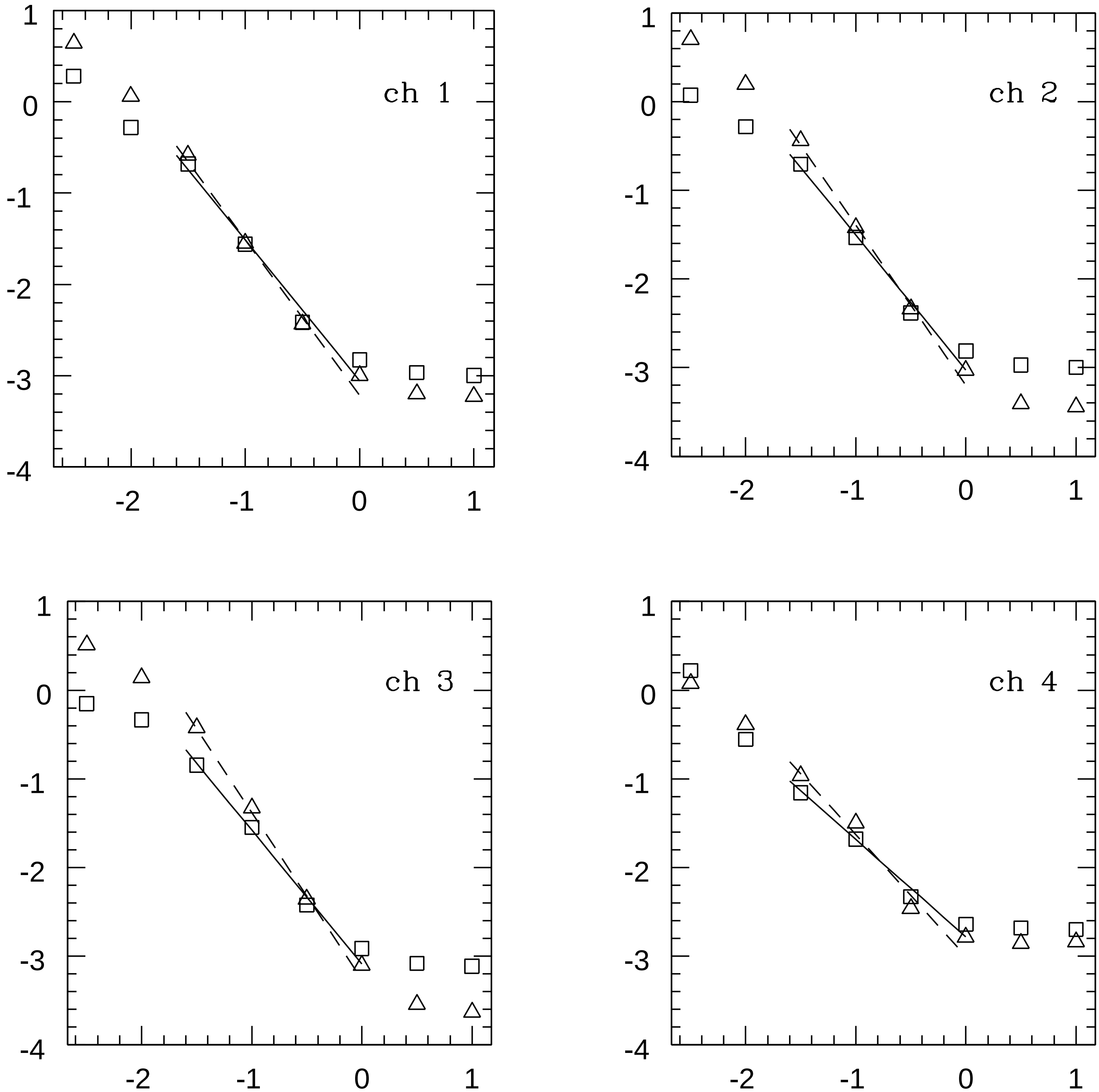
Fig. 2.— Similar plots as Figure 1, but light curves are rescaled by a factor of $1 + z$ to remove a time dilation effect before calculated PDSs.

Table 1: A list of the GRBs used in the analysis with the redshifts and peak fluxes. The redshifts are quoted from a complied table in $http://www.aip.de/\ jcg/grbgen.html$.

GRB name	trigger number	redshift	peak flux
GRB 000418	8079	1.118	1.6542
GRB 991216	7906	1.02	91.481
GRB 990510	7560	1.619	11.283
GRB 990506	7549	1.3	25.122
GRB 990123	7343	1.60	16.962
GRB 980703	6891	0.966	2.9310
GRB 980425	6707	0.0085	1.2451
GRB 980329	6665	3.9	13.848
GRB 971214	6533	3.42	2.6490
GRB 970508	6225	0.835	1.2816

Table 2: Obtained slopes with the least square fits for the two subgroups of far and near GRBs. Fittings are repeated before and after correction of a time dilation effect by a factor of $1 + z$.

	as-it-is		corrected	
channel	far	near	far	near
1	-1.7064 ± 0.115	-1.5436 ± 0.109	-1.5646 ± 0.149	-1.5082 ± 0.097
2	-1.8052 ± 0.101	-1.5220 ± 0.109	-1.5857 ± 0.144	-1.4652 ± 0.095
3	-1.8811 ± 0.103	-1.5105 ± 0.095	-1.6008 ± 0.159	-1.4160 ± 0.090
4	-1.3714 ± 0.127	-1.0989 ± 0.070	-1.3985 ± 0.150	-1.1130 ± 0.059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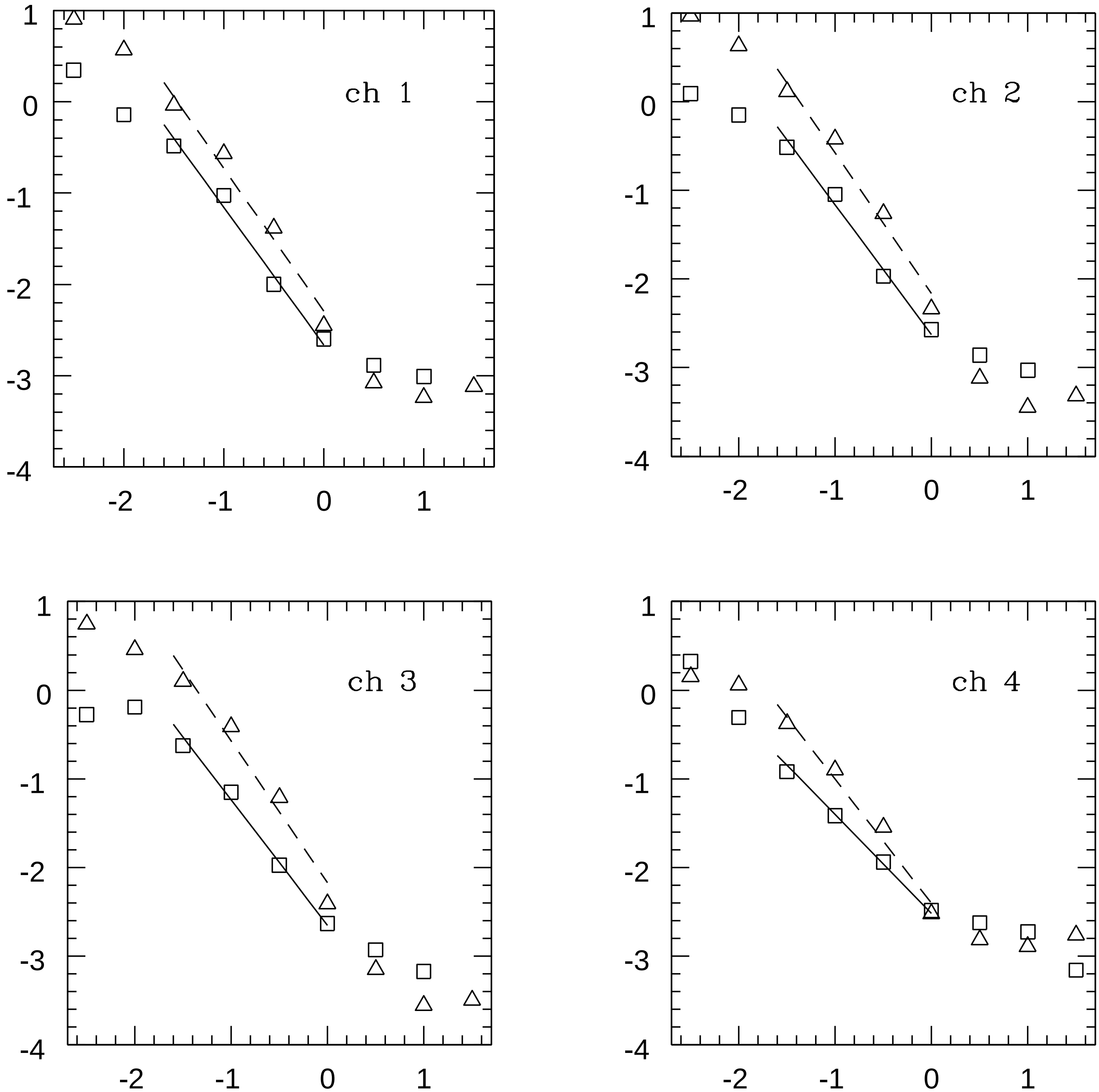
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